BOREHOLE ELECTROSEISMIC MEASUREMENTS IN DOLOMITE: IDENTIFYING FRACTURES AND PERMEABLE ZONES

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ABSTRACT

Measuring the electrical field induced by a borehole Stoneley wave is a new method for characterizing a rock formation around a borehole. Our field measurements demonstrate that the Stoneley-wave-induced electrical field can be detected in sedimentary rocks (dolomite in our experiment), and that the amplitude of this electroseismic phenomenon can be used to detect isolated fractures and permeable zones.

INTRODUCTION

Electroseismic phenomena allow direct observation of pore fluid flow driven through a rock formation by a seismic wave. Even though these seismic-wave-driven fluid flows are very small, it is possible to detect them in field experiments by measuring the streaming electrical fields that they induce. In turn, measurements of seismic-wave-induced pore fluid flows provide geophysicists with a new way to study rock properties.

Laboratory experiments (Zhu and Toksöz, 1997) and theoretical analysis (Haartsen, 1995; Mikhailov *et al.*, 1998) suggest that borehole electroseismic measurements can be used to detect permeable zones. Our study is aimed at determining the practical value of borehole electroseismic phenomena for geophysical exploration. We focus our investigation on the electrical fields induced by a borehole Stoneley wave. In this paper we first demonstrate that this phenomenon can be observed in sedimentary rock formations in the field. Further, we compare the results of our electroseismic measurements with the results of other geophysical measurements and show that the normalized amplitude of the Stoneley-wave-induced electrical field can be used to detect isolated fractures and permeable zones intersected by a borehole.

THE PHYSICAL PHENOMENON

A seismic-wave-induced flow of pore fluid through a rock can be detected in field experiments because the pore fluid in contact with a rock usually carries an excess electrical charge. This excess electrical charge is acquired by the pore fluid because pore surfaces of most minerals adsorb electrical ions when they are in contact with an electrolyte. For example, in quartz-bearing rocks saturated with water, pore surfaces adsorb negative ions, leaving an excess of positive ions in the pore fluid. Whenever a pressure gradient forces the pore fluid to flow through the rock, a streaming electrical current is carried by the fluid, thus allowing the flow to be detected.

The fact that the pore fluid carries electrical charges explains why seismic waves induce electrical fields when traveling through porous rocks. Figure 1 shows a diagram of an electrical field induced by a borehole Stoneley wave. A Stoneley wave traveling in a borehole creates a pressure gradient in the rock formation. This pressure gradient drives a pore fluid flow from the zone of compression to the zone of extension. If the bulk of the pore fluid carries a positive electrical charge, then the flow results in accumulation of a positive charge in the zone of extension, and a negative electrical charge in the zone of compression. This capacitor-like electrical charge separation travels along the borehole with the Stoneley wave, and creates an electrical field that moves along the borehole with the Stoneley wave velocity.

THE THEORETICAL MODEL

Theoretical analysis of the Stoneley-wave-induced electrical field suggests that porosity and permeability of a rock formation can be determined from borehole electroseismic measurements. Mikhailov (1998) used Pride's (1994) theory of dynamic streaming potentials to obtain an analytical solution for the ratio of the amplitude of the electrical field to the pressure oscillation in the borehole Stoneley wave:

$$\frac{E_z}{P_b} = \frac{\frac{\phi}{\alpha_\infty}\frac{\zeta\epsilon_f}{\mu}\left[-\frac{i\omega}{c_s}\right]\left[1-\frac{i\omega}{\omega_c}\right]^{-\frac{1}{2}}}{\sigma_r + \sigma_f \frac{I_1\left(R_b\frac{\omega}{c_s}\right)}{I_0\left(R_b\frac{\omega}{c_s}\right)}\frac{K_0\left(R_b\frac{\omega}{c_s}\right)}{K_1\left(R_b\frac{\omega}{c_s}\right)}}. \tag{1}$$

In Equation 1, ω is the Stoneley wave angular frequency, c_s is the wave velocity, ϕ is the porosity, α_∞ is the pore space tortuosity, ζ is the zeta-potential (determined by the electrochemical interaction between the pore fluid and the rock matrix), ϵ_f is the pore fluid permittivity, and ω_c is the Biot critical frequency for the formation, which depends on permeability of the formation k_0:

$$\omega_c = \frac{\phi_{ic}\mu}{\alpha_\infty \rho_f k_0} \cdot \frac{2}{M}. \tag{2}$$

Here, ρ_f is the density of the pore fluid, and the coefficient M is close to 1.0 for most media (Johnson *et al.*, 1987).

Equation 1 has two major implications. The first implication is that at a single frequency the amplitude of the electrical field is proportional to porosity. The second implication is that if the electroseismic measurements are done over a wide frequency range, then, in theory, it is possible to determine the Biot critical frequency for the formation. In turn, the Biot critical frequency is related to the formation permeability. Thus, the theory suggests that the borehole electroseismic phenomena yields a new way of determining porosity and permeability, provided that it is possible to measure the Stoneley-wave-induced electrical fields in practice.

FIELD EXPERIMENTS

To demonstrate that the Stoneley-wave-induced electrical field can be detected in sedimentary rocks, we conduct field experiments in boreholes drilled through dolomite at a site in Belvidere, Illinois. We chose this site for our experiments because it was well characterized by other geophysical measurements. The permeable zones in the subsurface at the site had been identified by wireline packer tests, borehole flowmeter measurements, and cross-borehole pumping tests (Paillet, 1997). Figure 2 presents a vertical cross section of the subsurface at the site. It shows four major permeable zones. The first zone is a permeable bedding plane intersecting boreholes T6 and T7 at the depth of 12 m. The second is a near vertical fracture intersecting boreholes T1 and T2 between the depths of 20 m and 30 m. The third and fourth are porous zones intersecting all boreholes at the site at depths of around 30 m and 45 m, respectively. Knowledge of the locations of the permeable zones and isolated fractures at the site allows us to test whether the Stoneley-wave-induced electrical fields can be used for detecting these zones, as the theoretical analysis suggests.

During our field experiment, we generate a borehole Stoneley wave at the top of the well by striking the casing with a sledgehammer. We measure the pressure oscillations in the well using hydrophones. Electrical fields are measured as a potential difference between two lead electrodes separated vertically by $0.5m$ distance (Figure 3). During the experiments, the electrodes are suspended freely in the borehole fluid and connected to the data acquisition system at the surface by a non-armored cable. To obtain measurements throughout the entire uncased section of the well, we place the electrodes at different depths and repeat the seismic source. A more detailed description of this experimental procedure and the noise reduction processing is given in Mikhailov *et al.*. (1997) and Mikhailov *et al.* (1998).

FIELD DATA

The electroseismic field data collected in our experiment shows that the Stoneley-wave-induced electrical field can be measured in dolomite. Figure 4a shows the hydrophone measurements of the direct Stoneley wave in borehole T1. Figure 4b shows the electrical field measurements in borehole T1. Two events are present in the electrical data. The first is an electromagnetic wave generated at time zero by striking the metal casing with a metal sledgehammer. This wave travels with the speed of light, and arrives "simultaneously" at all depths at time zero. The second event present in the data is the oscillation of the electrical field traveling along the borehole together with the Stoneley wave.

Later in this paper we analyze the normalized amplitude of this Stoneley-wave-induced electrical field and show that the maximum amplitudes of these fields are observed in permeable zones and around isolated fractures. This observation leads us to believe that the electroseismic phenomenon we are observing is the electrical field caused by Stoneley wave induced pore fluid flow in permeable zones around the formation.

We define the normalized amplitude of the Stoneley-wave-induced electrical field as the ratio of the amplitude of the electrical field oscillation at a certain depth to the amplitude of pressure oscillation at the same depth. Figures 5, 6, 7, and 8 present the plots of the amplitudes of the pressure oscillations in the Stoneley wave recorded by hydrophones, electrical potential oscillations recorded by electrode pairs, and the normalized amplitudes of the Stoneley-wave-induced electrical fields measured in boreholes T1, T2, T6, and T7 respectively. The analysis of these amplitudes for each borehole is given below.

Borehole T1

Wireline packer tests, borehole flowmeter measurements and cross-borehole pumping tests demonstrate that borehole T1 intersects an isolated fracture and several permeable zones. These zones, however, cannot be identified in the neutron porosity log or acoustic log. Figure 9 shows the caliper, the P-wave slowness log and the neutron porosity log for the borehole T1. The porosity log in Figure 9 does not show any significant variation along the entire depth of investigation, and thus does not give any indication of the locations of the permeable zones. The numerous vugs that constitute a significant portion of the dolomite's porosity may cause this lack of variation in the porosity. The caliper and borehole televiewer logs demonstrate that the dolomite formation around the borehole has so many vugs that in some zones the formation resembles swiss cheese. While contributing to the total porosity, the vugs do not necessarily contribute to permeability. Therefore, borehole T1 presents an interesting challenge to our electroseismic research because it tests whether the electroseismic measurements are capable of distinguishing disconnected porosity from connected porosity.

Figure 10 shows that the normalized amplitude of the Stoneley-wave-induced electrical field in Figure 10a has peaks at depths of 23 m, 27 m, 28 m, 32 m, 40 m, 48 m, and 57 m. At the depth of 23 m, borehole televiewer measurements show an isolated fracture intersecting the well. Wireline packer measurements show permeable zones at depths around 23 m, 28 m, 38 m, and 58 m. Also, at these depths borehole flowmeter shows changes in the vertical velocity of the stationary fluid flow in the borehole. These changes indicate a flow of fluid in or out of the formation. Thus, in borehole T1 the results of the electroseismic measurements correlate with other geophysical measurements and indicate permeable zones.

Borehole T2

Figure 11 shows that in borehole T2 the Stoneley-wave-generated electrical fields have a sharp peak at the depth of 20 m. At this depth, the borehole televiewer log shows an isolated fracture intersecting the borehole. The borehole flowmeter also shows that at this depth borehole fluid flows out of the formation. This result demonstrates that the amplitude of the Stoneley-wave-induced electrical field can be used as an indicator of isolated fractures.

Borehole T6

In borehole T6 we could not make measurements of the electrical fields induced by the Stoneley wave in the permeable bedding plane at the depth of 12 m, because it was too close to the casing. The electromagnetic wave generated by the casing obscured the electroseismic signal of interest. Figure 12 shows that below the depth of 12 m the amplitude of the Stoneley-wave-induced electrical fields have a single sharp peak at the depth of 49 m. This peak might correspond to the permeable zone identified by the wireline packer around the depth of 48 m. However, in the other permeable zones detected by the packer around the depths of 28 m, 38 m, and 53 m, the Stoneley-wave-induced electrical field does not generate electrical fields with amplitudes significantly higher than in the rest of the borehole.

Nevertheless, the results of the experiment in borehole T6 are not disappointing, since a comparison can be made between the average amplitude of the Stoneley-wave-induced electrical fields and the neutron porosity log for this borehole. Figure 13 shows the plots of the averaged amplitude of the electroseismic signals, the averaged neutron porosity log for borehole T6, and the P-wave slowness log. Figure 13 shows that the porosity and the Stoneley-wave-induced electrical field's amplitudes have similar trends. This observation again supports our theoretical analysis that the amplitude of the Stoneley-wave-induced electrical field is proportional to the porosity of the formation.

Borehole T7

As with borehole T6, we cannot investigate the permeable bedding plane in borehole T7 because of its close proximity to the casing. Figure 14 shows the normalized amplitudes of the Stoneley-wave-induced electrical fields measured below the 12 m depth. This normalized amplitude varies along the borehole by a factor of 5, being the lowest in the zone around 20 m and the highest in the interval from 40 m to 60 m. The only permeability indication available for this borehole is the borehole flowmeter measurements. The flowmeter shows that in the interval around the depth of 20 m, the velocity of the downflow of the borehole fluid does not change with depth, indicating that there is no flow of the fluid in or out of the formation, suggesting low permeability. At the same time, in the depth interval from 40 m to 60 m the velocity of the fluid flow decreases with depth, indicating an inflow of the borehole fluid into the formation. This observation indicates that the formation at this depth interval is permeable. This qualitative comparison again supports our claim that the amplitudes of the Stoneley-wave-induced electrical field can be used as an indicators of permeable zones.

DISCUSSION

Our field data illustrate two interesting features of the Stoneley-wave-induced electrical field. First, it appears that the amplitude of the phenomenon is sensitive to porosity rather than permeability. In the borehole T1, the highest E/P values are measured at 30 m, where relative hydraulic transmissivity is 30 times lower than that of the vertical fracture at around 25 m. Second, the amplitude of the Stoneley-wave-induced electrical field varies in the borehole T1 only by a factor of five. At the same time, the neutron porosity log in Figure 9 shows no significant variations of the total porosity. In borehole T6, the amplitude of the Stoneley-wave-induced electrical fields follows the same trend as the neutron porosity log. However, while the value of the total porosity in Figure 13 varies only by 25 percent, the electroseismic signal's amplitudes vary by a factor of four. We suggest the following explanation for these observations. The electrical fields measured in the experiments are generated by the pore fluid flow, therefore the amplitude of the electrical field should be sensitive only to the interconnected part of the total porosity, i.e., the volumetric fraction of rock through which the fluid can flow. On the other hand, this hypothesis, though, needs to be confirmed by further experiments.

CONCLUSIONS

Measurement of the electrical field induced by a borehole Stoneley wave is a new type of geophysical measurement. Our field measurements show that the Stoneley-wave-induced electrical fields can be measured in sedimentary rocks (dolomite). Further, our results demonstrate that a Stoneley wave generates stronger electrical fields in permeable zones, thus suggesting that electroseismic measurements can be used for detecting them.

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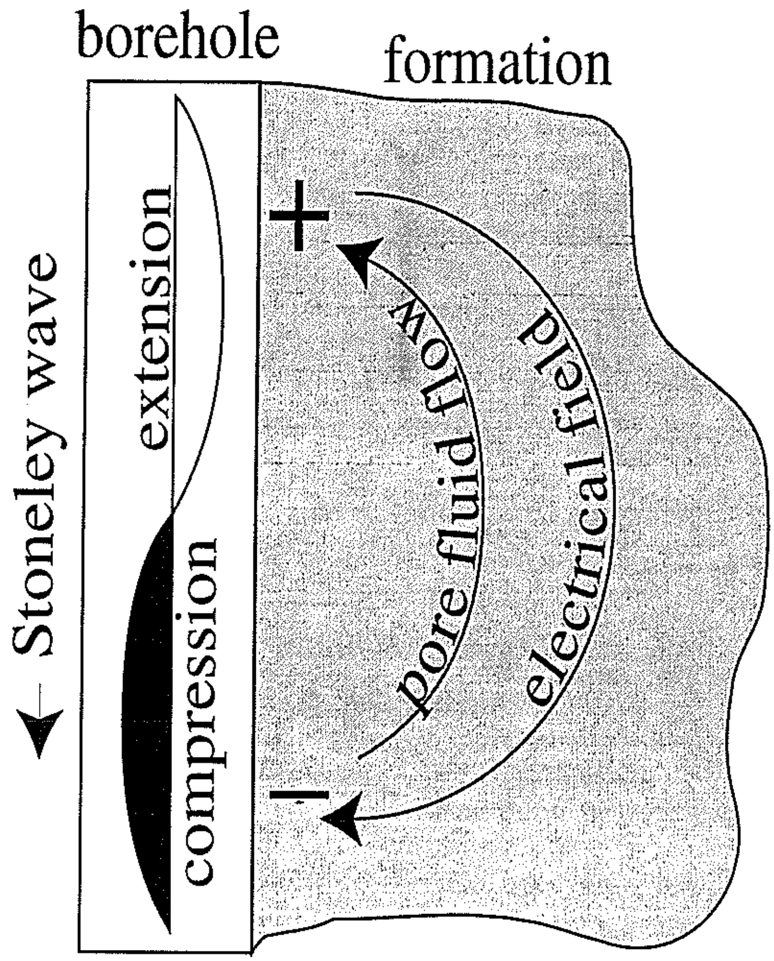

Figure 1: Diagram of a Stoneley wave inducing an electrical field. When a Stoneley wave travels along a borehole in a permeable formation, it generates a flow of pore fluid within the formation from the zone of compression to the zone of extension. If the pore fluid carries a positive electrical charge, the flow of pore fluid creates accumulation of a positive charge in the zone of extension and a negative charge in the zone of compression. This capacitor-like charge separation travels along the borehole together with the seismic wave, and induces electrical fields that are contained within the Stoneley wave pulse.

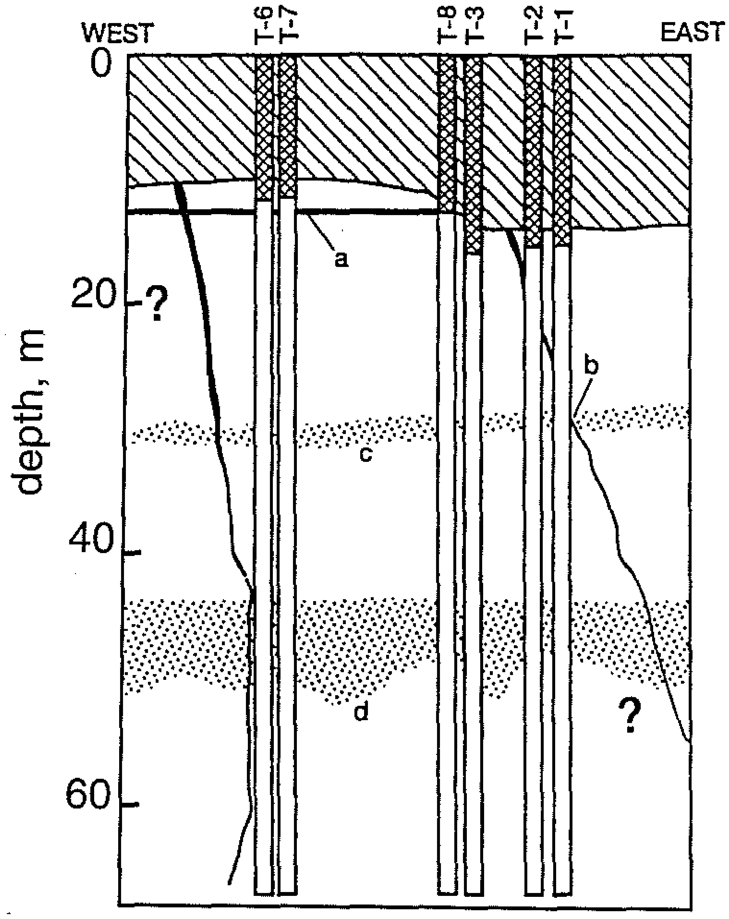

Figure 2: A vertical cross section of the subsurface at the site in Belvidere, Illinois, showing the locations and connectivity of permeable zones and fractures. Figure (a) is a permeable bedding plane, (b) is a nearly vertical fracture, (c) and (d) are porous permeable zones. We made electroseismic measurements in wells T1, T2, T6 and T7.

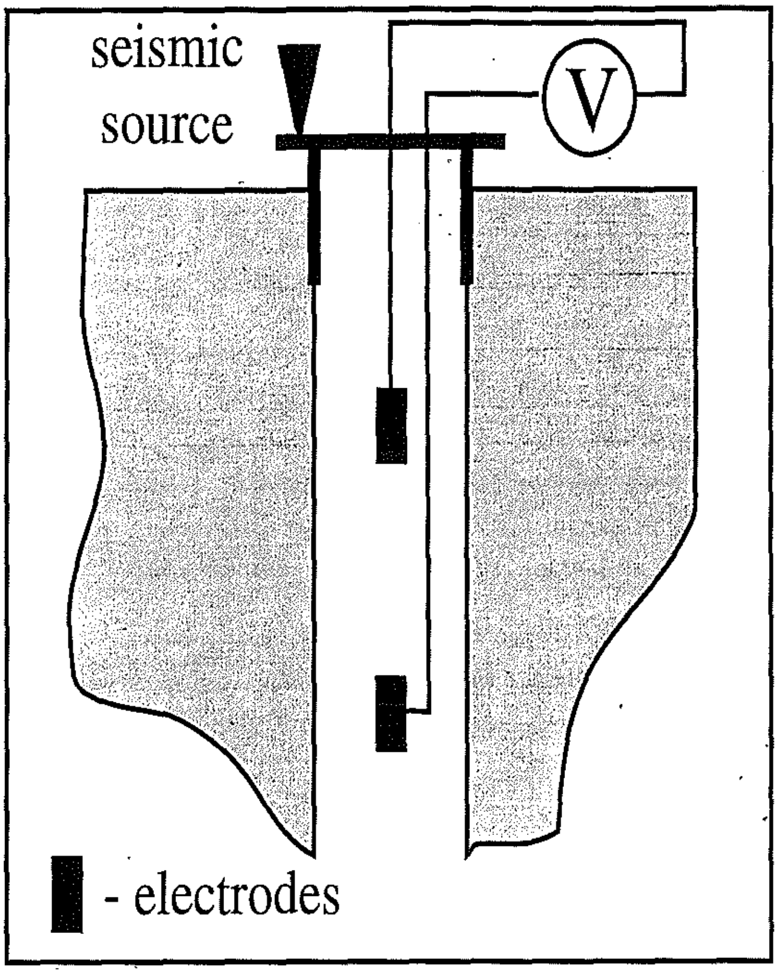

Figure 3: Diagram of the electrical field measurements. During the experiments we measured the electrical field induced by a Stoneley wave as a potential difference between two lead electrodes suspended in the borehole fluid. The electrodes were connected to the data acquisition system at the surface by an unarmored cable. In the experiment the Stoneley wave was generated by striking the casing with a sledgehammer.

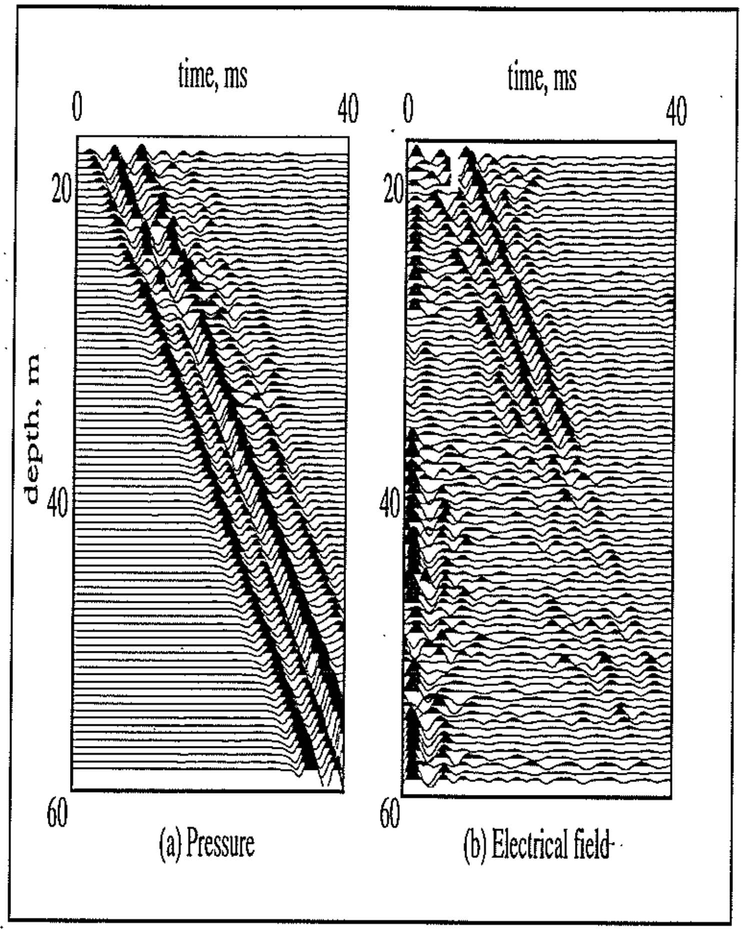

Figure 4: Results of the hydrophone and the electrical measurements in borehole T1. The electrical data show an electrical signal traveling along the borehole together with the Stoneley wave. This signal is the electrical field induced by the Stoneley-wave-driven flows of pore fluid within permeable formations around the borehole. The electrical signal arriving simultaneously at all depths at time zero is the electromagnetic wave generated by striking a metal casing with a metal sledgehammer.

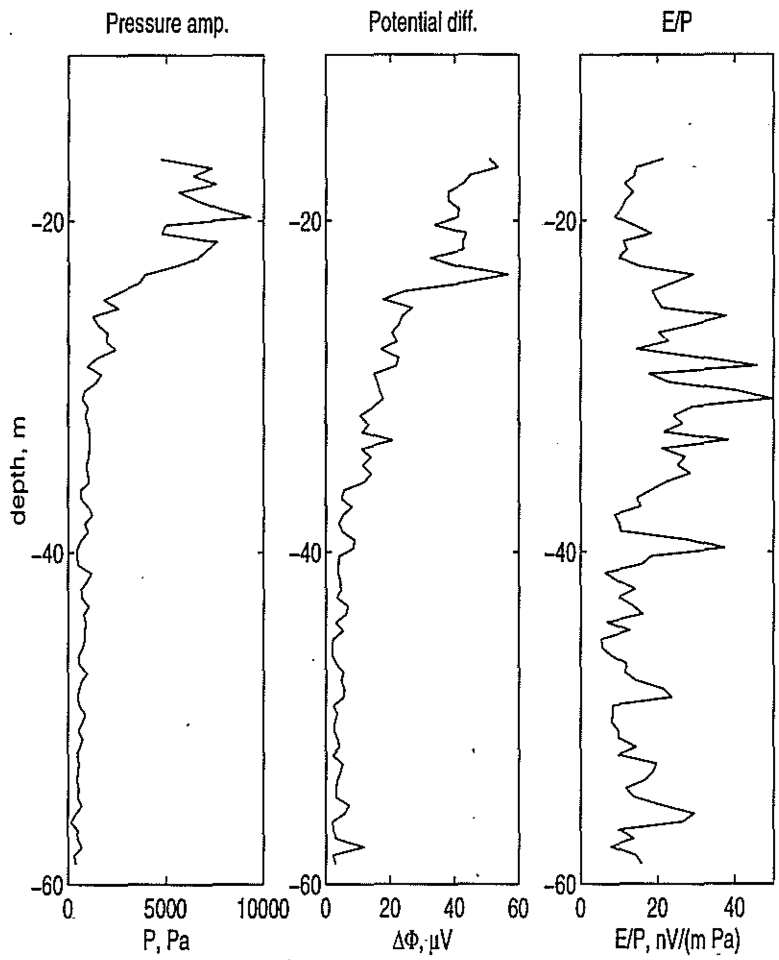

Figure 5: Amplitudes of the pressure and electrical potential oscillation generated by the Stoneley wave in borehole T1. The normalized amplitude of the Stoneley-wave-induced electrical field is defined as the ratio of the amplitude of the electrical potential oscillation to the amplitude of the pressure oscillation at the same depth. We propose to use measurements of this ratio for detection of permeable zones and isolated fractures.

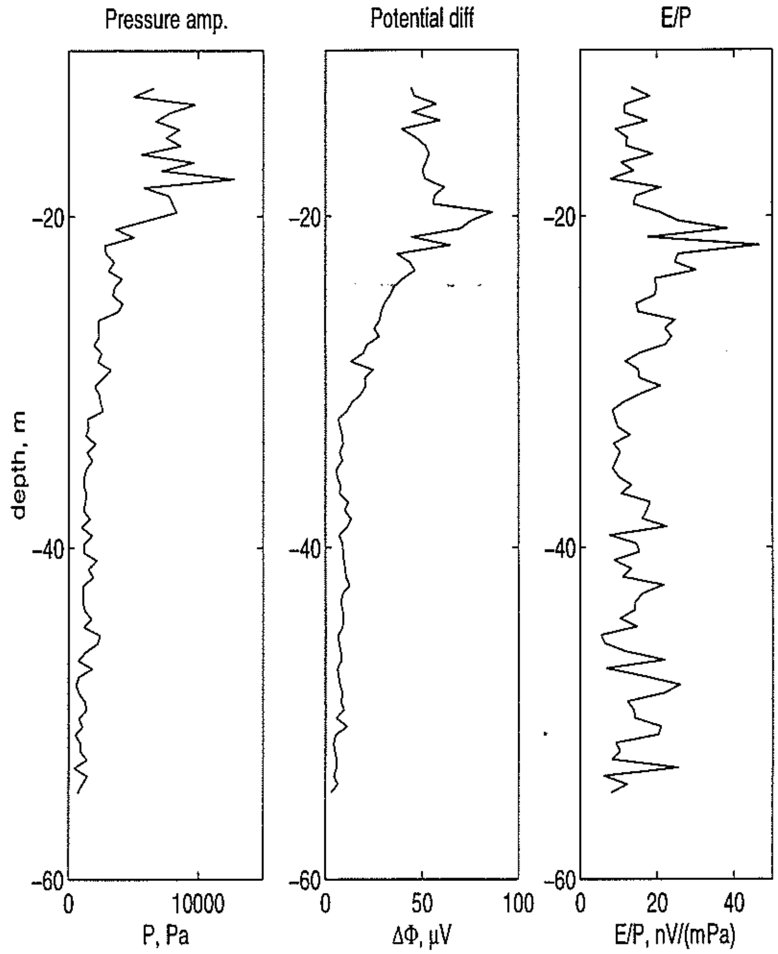

Figure 6: Amplitudes of the pressure and electrical potential oscillation generated by the Stoneley wave in borehole T2. The normalized amplitude of the Stoneley-wave-induced electrical field is defined as the ratio of the amplitude of the electrical potential oscillation to the amplitude of the pressure oscillation at the same depth. We propose to use measurements of this ratio for detection of permeable zones and isolated fractures.

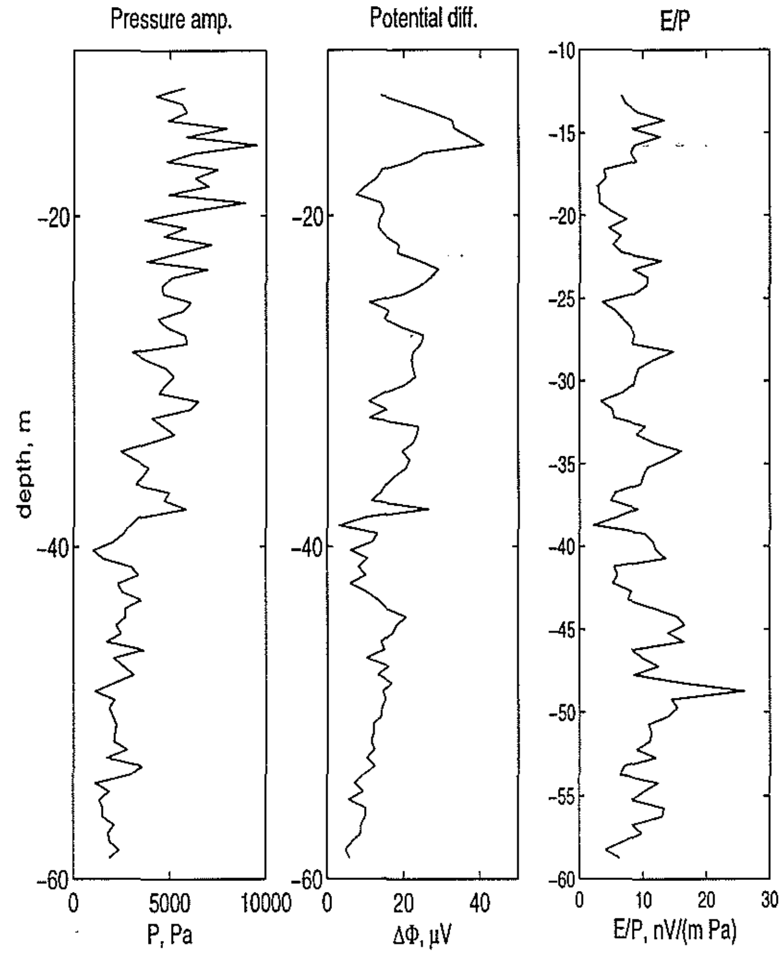

Figure 7: Amplitudes of the pressure and electrical potential oscillation generated by the Stoneley wave in borehole T6. The normalized amplitude of the Stoneley-wave-induced electrical field is defined as the ratio of the amplitude of the electrical potential oscillation to the amplitude of the pressure oscillation at the same depth. We propose to use measurements of this ratio for detection of permeable zones and isolated fractures.

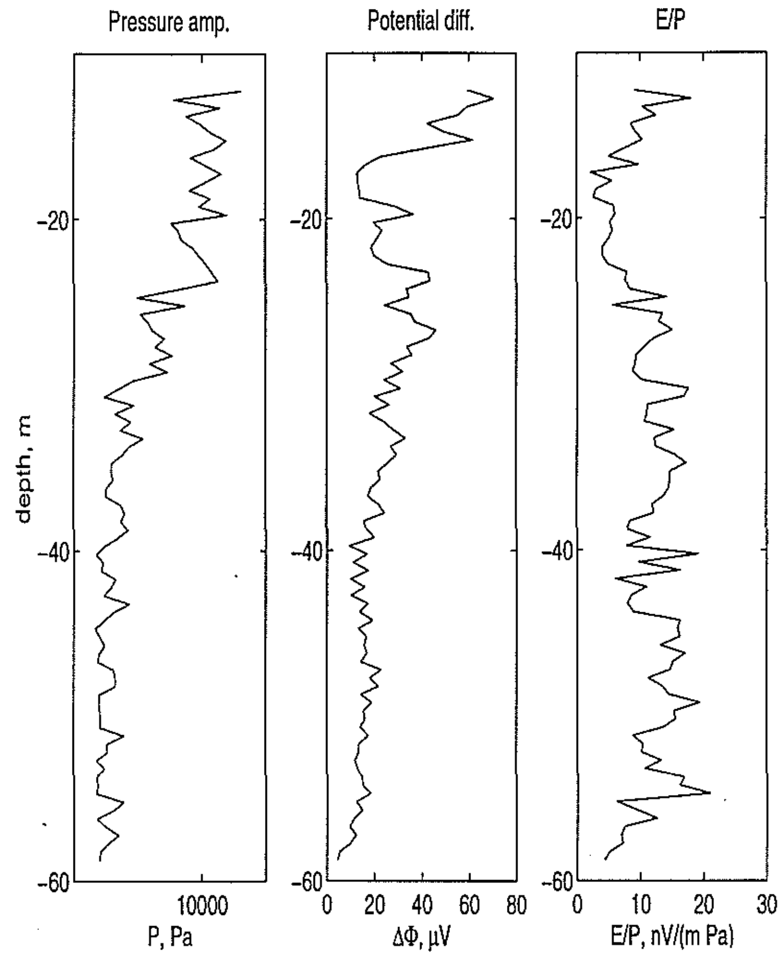

Figure 8: Amplitudes of the pressure and electrical potential oscillation generated by the Stoneley wave in borehole T7. The normalized amplitude of the Stoneley-wave-induced electrical field is defined as the ratio of the amplitude of the electrical potential oscillation to the amplitude of the pressure oscillation at the same depth. We propose to use measurements of this ratio for detection of permeable zones and isolated fractures.

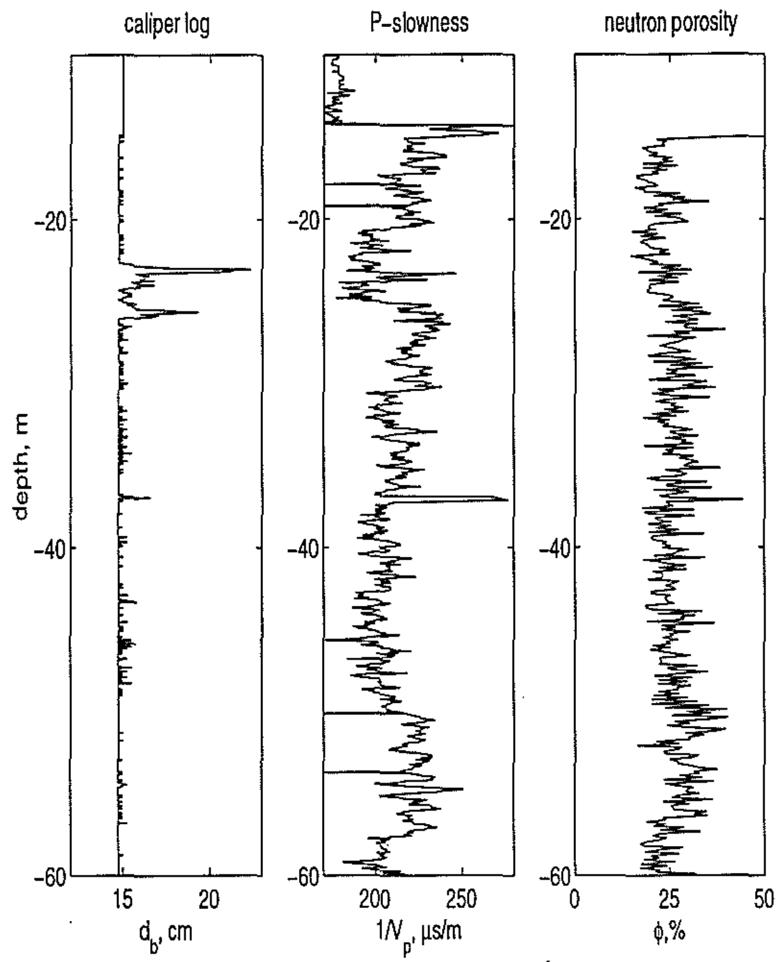

Figure 9: Caliper, P-wave slowness and neutron porosity logs for the well T1. In the caliper log the vertical fracture intersecting the well at the depth of 25 m is detected. Neutron porosity log shows only slight variations and cannot be used to detect permeable zones.

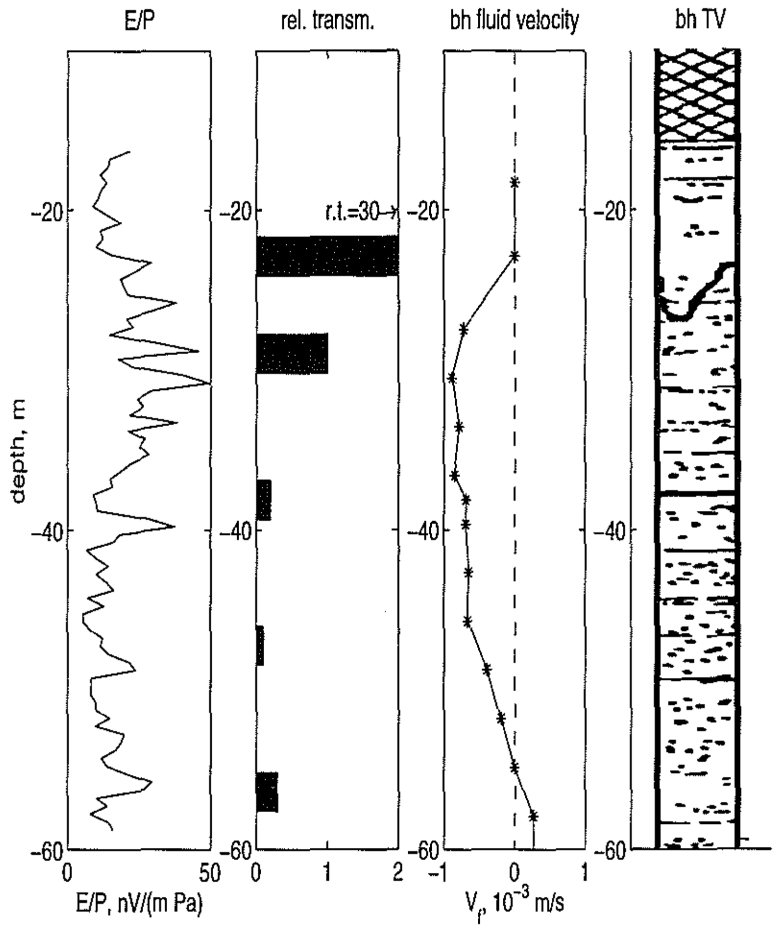

Figure 10: Comparison of the normalized amplitude of the Stoneley-wave-induced electrical fields to the results of wireline packer, borehole flowmeter and borehole televiewer measurements, that identify the isolated fracture and other permeable zones intersected by the borehole T1. Electroseismic signals have sharp peaks of amplitude in the permeable zones.

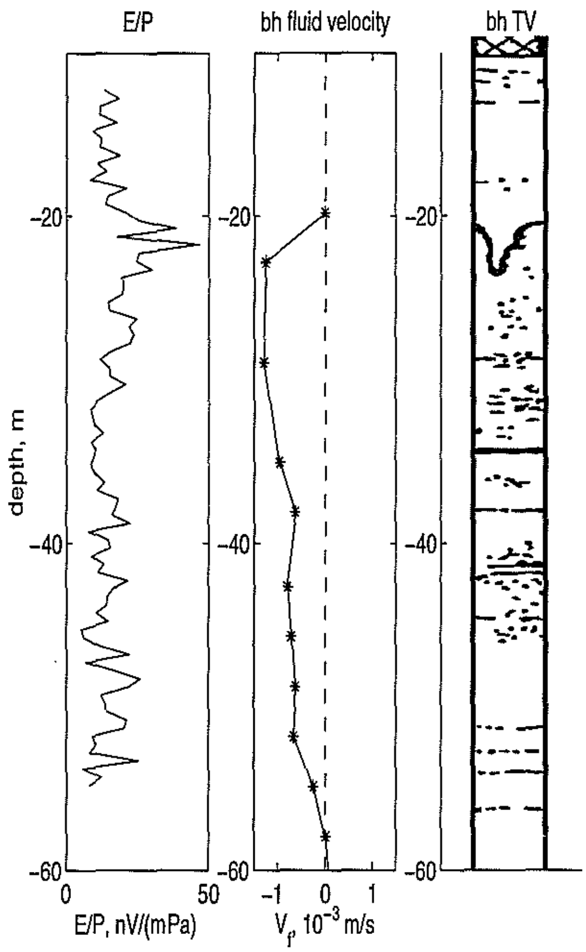

Figure 11: Comparison of the normalized amplitude of the Stoneley-wave-induced electrical fields to the results of borehole flowmeter and borehole televiewer measurements in the well T2. The electroseismic signals detected in our experiments have a sharp peak of the amplitude at the depth of the fracture.

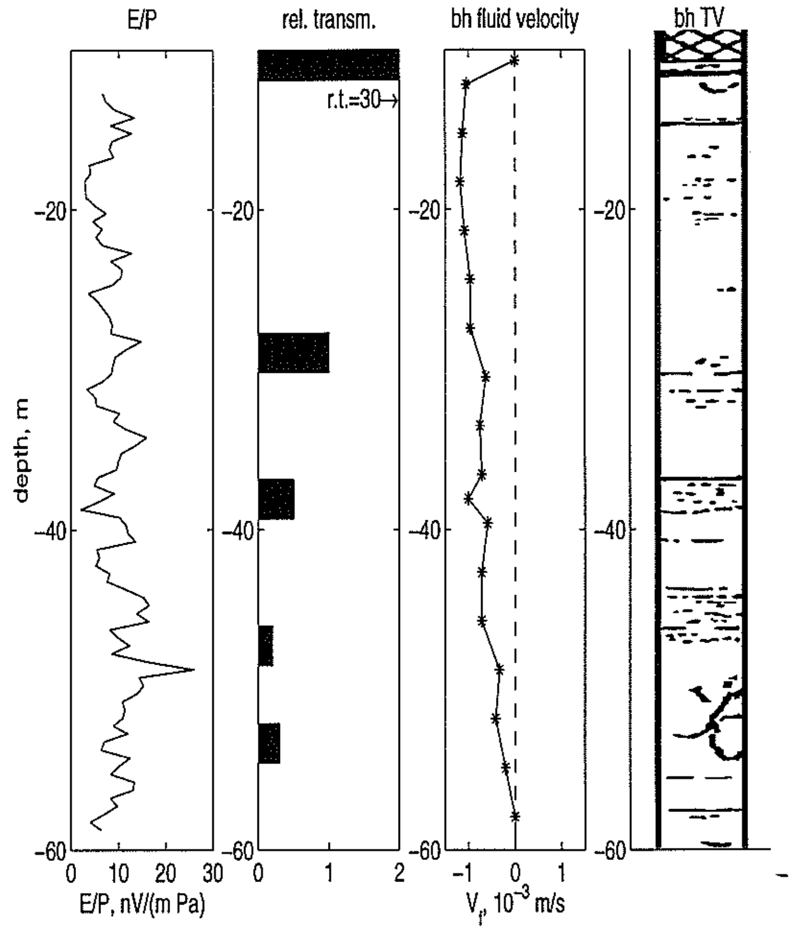

Figure 12: Comparison of the normalized amplitude of the Stoneley-wave-induced electrical fields to the results of wireline packer, borehole flowmeter and borehole televiewer measurements in the borehole T6. Electroseismic signals do not have significant peaks of amplitude associated with permeable zones around the depths of 28 m, 38 m and 53 m.

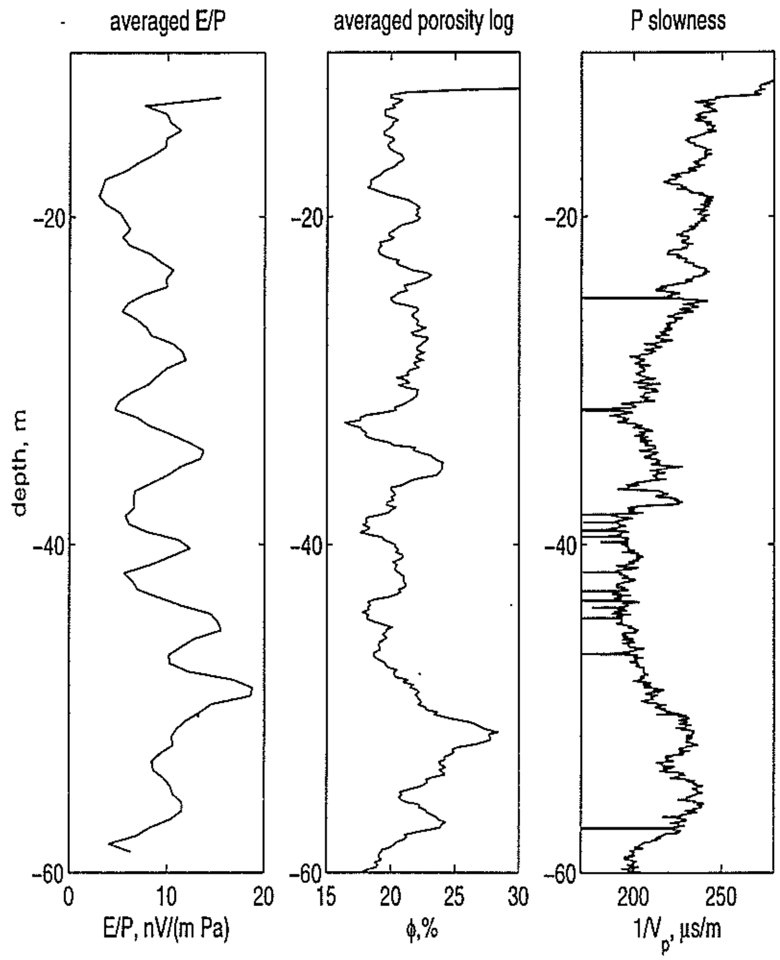

Figure 13: Comparison of the averaged amplitude of the Stoneley-wave-induced electrical field to the neutron porosity and acoustic logs in the borehole T6. The electroseismic signals' amplitudes show the same trend as the porosity measurements. This observation supports our theoretical analysis that the amplitude of the Stoneley-wave-induced electrical field is proportional to porosity.

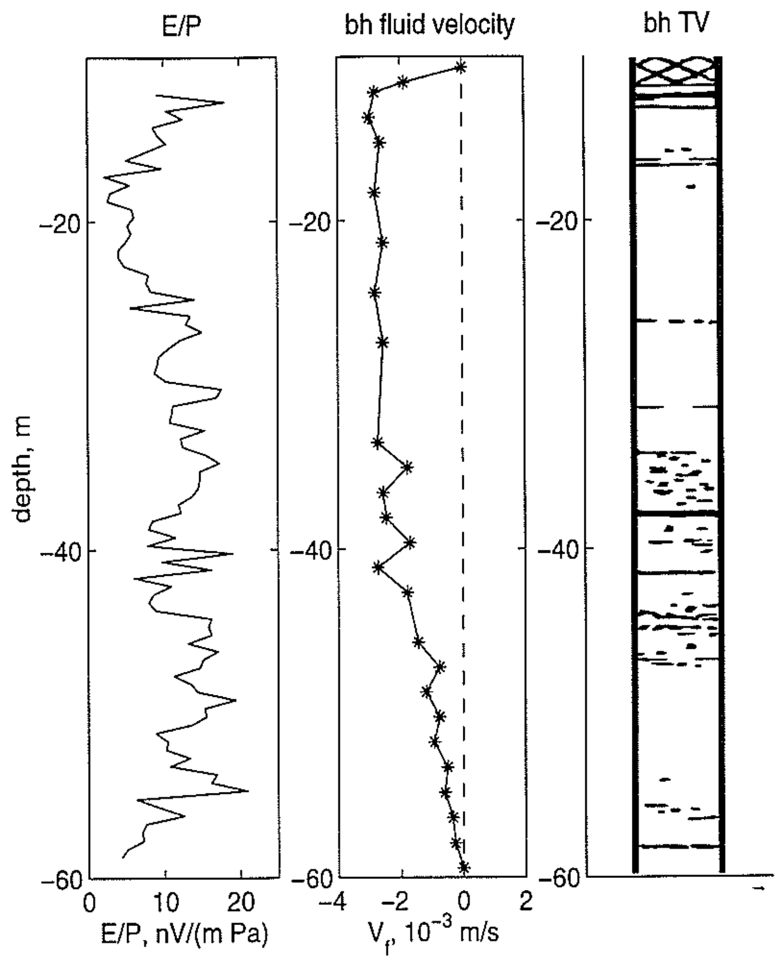

Figure 14: Comparison of the normalized amplitude of the Stoneley-wave-induced electrical fields to the results of wireline packer, borehole flowmeter and borehole televiewer measurements, that identify the isolated fracture and other permeable zones intersected by the borehole T7. Borehole flowmeter measurements show an inflow of borehole fluid into the formation between the depths of 40 m and 60 m, indicating that this interval is permeable. The Stoneley-wave-induced electrical fields have relatively higher amplitudes in these zones. This result is consistent with our model of the Stoneley-wave-induced electrical field.